Experimental study of two-phase pressure drop of corrugated mini channel

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1. Introduction

The flow of steam-water mixtures within the steam generator is extremely complex as a two-phase flow, and two-phase flow pressure drop is important for system safety. If the pressure inside the system is reduced due to a two-phase flow pressure drop, the heat transfer efficiency of the steam generator will be reduced. Pressure loss caused by two-phase flow also affects controls that govern the movement and heat transfer of substances within the system, which can also lead to safety concerns.

Accordingly, research on the field of two-phase flow pressure drop inside the steam generator is continuously being conducted. Various experiments and numerical analyses are used in this field, including pressure drop measurement and prediction. These techniques contribute to improving system safety and power generation efficiency.

Since the 2000s, various studies have been conducted in the field of two-phase flow pressure drop of steam generators in nuclear power plants. Advances in numerical analysis have made it possible to accurately predict the flow phenomenon inside the steam generator. This led to the prediction of a two-phase flow pressure drop inside the steam generator and the improvement of the design to reduce it.

In addition, two-phase flow pressure drop experiment technology has also advanced. An experimental facility was developed that took into account the properties of mixture flow inside the steam generator, which led to the collection and analysis of experimental data. These methods have led to a more accurate understanding of flow phenomena within the steam generator. They have also led to the development of response plans to mitigate heat transfer reduction caused by two-phase flow pressure drop.

Furthermore, with the development of artificial intelligence technology, AI is being used in the prediction and analysis of two-phase flow pressure drop. For example, a two-phase flow pressure drop prediction model using deep learning has been developed and applied.

The development and research of various technologies continue to drive efforts to improve safety and power generation efficiency. These efforts are focused even in the field of two-phase flow pressure drop within the steam generator.

Numerous experiments have been conducted in the field of two-phase flow pressure drop in steam generators in nuclear power plants.

A study by Ide et al. (2007) experimentally investigated the fundamentals of gas-liquid two-phase flow in a mini channel [1]. The experiment confirmed that in a mini channel, less than 5mm diameter tube, surface tension is more governing than buoyancy force. So, In horizontal flow, the gas bubble is axis-symmetric and the liquid film is symmetrically observed.

Kim et al. (2010) Investigated the hydraulic performance of a micro-channel PCHE [2]. The hydraulic performance on the longitudinal corrugation flow channel was predicted by computational fluid dynamics (CFD) simulation and validated by experimental data.

2. Methods and Experimental Apparatus

An experimental apparatus was used to conduct a two-phase flow pressure drop experiment, as shown in Fig. 1. Boiling phenomena were depicted using water and air, and a 3-bar air compressor was used to mix the air and atmospheric pressure water, which was then injected into the test section to create a vertical flow on the ground. The test section was made of acrylic, and its geometrical information is shown in Fig. 2. After the initial mixing zone (10 mm), the flow was divided into left and right sections and then mixed again. The channel thickness was 2.5 mm in total, with 1.25 mm thick plates symmetrically overlaid. This design enables a high heat transfer coefficient. Additionally, the internal pin of the test section increased the contact area and has advantages in diffusion bonding conditions for making printed circuit heat exchangers.

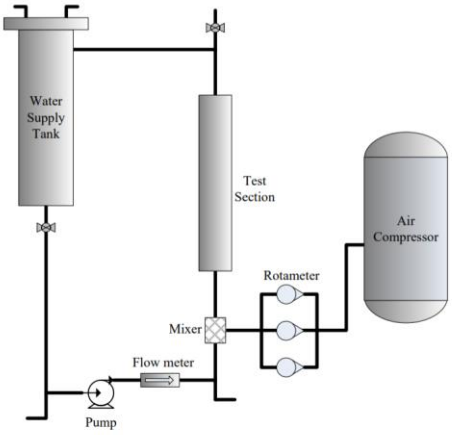


Fig 1. Experimental system

The total length of the test section is 1700mm, and there is a pressure port located at a height of 400mm and 1400mm, respectively, from the entrance of the test section. To reduce the uncertainty of the velocity fully developed region, pressure was measured at a location more than 10 times the hydraulic diameter, i.e., higher than 24.4mm. A pressure drop corresponding to 1000mm was measured in this experiment. Prior to conducting the two-phase flow experiment, a single-phase pressure drop experiment was conducted to distinguish between the laminar and turbulent flow regions. In the single-phase pressure drop experiment using a corrugated channel, water at room temperature and atmospheric pressure was used, and experiments were conducted in the Reynolds number range of 412 to 3110.

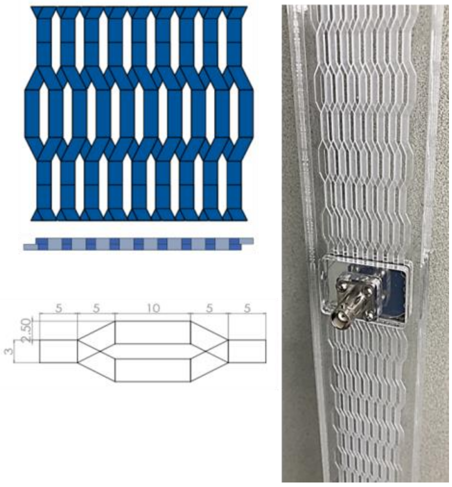


Fig 2. Test section Geometry

To measure the pressure drop, a differential pressure transmitter capable of measuring up to 300 kPa was used. The water flow rate was measured using a turbine flow meter, and two flow meters with flow rates ranging from 0.1 to 2.5 LPM and 1.0 to 10 LPM were used to improve the accuracy depending on the experimental conditions. For air, an MFM (mass flow meter) was used according to the experimental conditions, and sensors with ranges of 0-1 LPM, 0-10 LPM, and 0-100 LPM were used. In the two-phase flow experiments, liquid Reynolds numbers were tested in the range of 338 to 2366, and gas Reynolds numbers were tested in the range of 11 to 457.

3. Results and Discussion

In the single-phase flow pressure drop experiment, the laminar flow region could not be observed even in 300 Reynolds regions. This can be inferred by turbulentization caused by periodic mixing zone. Compared to the cylindrical 64/Re, a high single-phase friction factor could be confirmed. It can be seen that this causes a bigger pressure drop by the pin inside the test section.

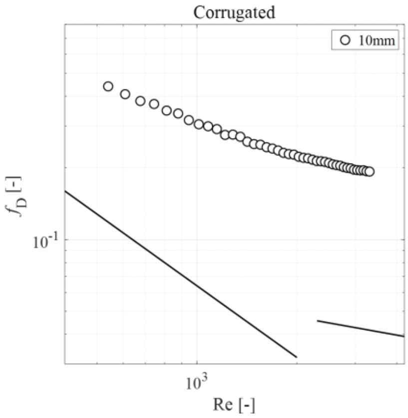


Fig 3. Single-phase friction factor

Based on this, the results of the two-phase flow experiment were analyzed and are shown in Fig 4. Fig 4(a) compares the Lockhart & Martinelli correlation, one of the most widely used correlations in the two-phase flow pressure drop experiments, with a plot using the Martinelli parameter to confirm the trend [3]. The Martinelli parameter is the ratio of the liquid pressure drop to the gas pressure drop, and a higher value indicates similarity to a single liquid phase, while a lower value indicates similarity to a single gas phase.

Although the difference in friction multiplier between the largest and smallest Martinelli parameters within the experimental range is not significant, there is some difference from the correlation, with an error of 53.76%. Fig. 4(b) applies the generalized equation obtained from thousands of data points from various experiments to create a common correlation for two-phase flow pressure drop, which was then compared with this study. A total of 36.13% error was observed, and Table 1 shows the Chisholm parameter values used in each correlation.

Table 1. Two-phase multiplier - Chisholm parameter
(a) Lockhart & Martinelli [3]

Liquid	Gas	C
Laminar	Laminar	5
Laminar	Turbulent	12
Turbulent	Laminar	10
Turbulent	Turbulent	20

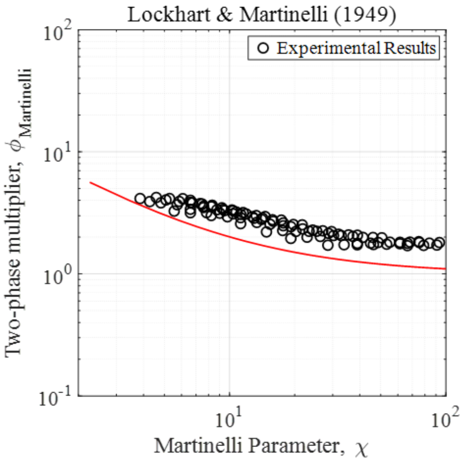
(b) Kim and Mudawar [4]

Liquid	Gas	C
Laminar	Laminar	$3.5 * 10^{-5} Re_{Lo}^{0.44} Su_{go}^{0.5} \left(\frac{\rho_L}{\rho_G}\right)^{0.48}$
Laminar	Turbulent	$0.0015 * Re_{Lo}^{0.59} Su_{go}^{0.19} \left(\frac{\rho_L}{\rho_G}\right)^{0.36}$
Turbulent	Laminar	$8.7 * 10^{-4} Re_{Lo}^{0.17} Su_{go}^{0.5} \left(\frac{\rho_L}{\rho_G}\right)^{0.14}$
Turbulent	Turbulent	$0.39 * Re_{Lo}^{0.03} Su_{go}^{0.10} \left(\frac{\rho_L}{\rho_G}\right)^{0.35}$

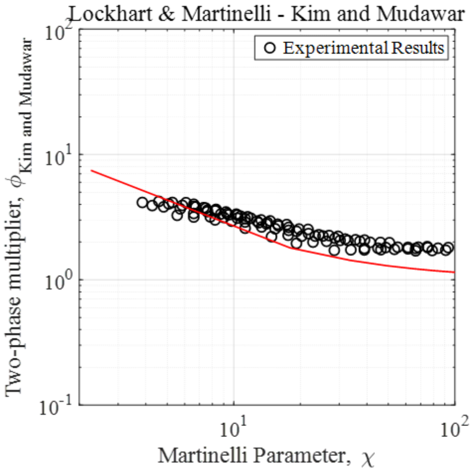
$$Re_{Lo} = \frac{GD_h}{\mu_L},\ Su_{Go} = \frac{\rho_G \sigma D_h}{\mu_G^2}$$

- G: total mass flux
- σ: surface tension
- μ: viscosity
- D_h: hydraulic diameter
- ρ: density

Where subscript *Lo* is liquid only single-phase state, *G* is gas, *L* is liquid.



(a) Lockhart & Martinelli



(b) Kim and Mudawar

Fig 4. Experimental Two-phase friction factor

In Fig 4(b), it can be seen that the error in the region where the liquid pressure drop is dominant with a high Martinelli parameter was similar to Fig 4(a), but in the low Martinelli parameter region where the gas pressure drop is dominant, it was found that the Kim and Mudawar correlation and experimental results were similar.

3. Conclusions

The two-phase flow pressure drop experiment was conducted in a corrugated mini channel. Prior to the two-phase multiplier measurement experiment, a single-phase friction coefficient measurement experiment was performed based on the results obtained. The single-phase pressure drop was tested in a Reynolds number range of 412 to 3110, while the two-phase friction multiplier was tested in a range of liquid Reynolds numbers from 338 to 2366 and gas Reynolds numbers from 11 to 457. It was difficult to observe the laminar region in the single-phase flow experiment, and in the two-phase region, two correlations were compared. Kim and Mudawar's correlation had less error than Lockhart & Martinelli correlation, and in the Martinelli parameter range of the two-phase region, it was found that the agreement between the correlation and experimental results was higher in the liquid-dominant region.

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REFERENCES

[1] Ide, H., Kariyasaki, A., & Fukano, T. (2007). Fundamental data on the gas–liquid two-phase flow in minichannels. International Journal of Thermal Sciences, 46(6), 519-530.
[2] Kim, J. H., Baek, S., Jeong, S., & Jung, J. (2010). Hydraulic performance of a microchannel PCHE. Applied Thermal Engineering, 30(14-15), 2157-2162.
[5] Lockhart, R. W. (1949). Proposed correlation of data for isothermal two-phase, two-component flow in pipes. Chem. Eng. Prog., 45, 39-48.
[6] Kim, S. M., & Mudawar, I. (2012). Universal approach to predicting two-phase frictional pressure drop for adiabatic and condensing mini/micro-channel flows. International Journal of Heat and Mass Transfer, 55(11-12), 3246-3261.